DTIC FILE COPY

AD-A222 263

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
APR 1990

3. REPORT TYPE AND DATES COVERED
FINAL, 1985 TO 1989

4. TITLE AND SUBTITLE
AERODYNAMIC/DYNAMIC INTERACTION

5. FUNDING NUMBERS
AFOSR 85-0158

2

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR-TR- 90-0554

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
DIRECTORATE OF AEROSPACE SCIENCES
BOLLING AFB, WASHINGTON D.C. 20332 NA

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
61102F
2307 A1

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE
DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
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[illegible] systems interactions; Vorticity;

14. SUBJECT TERMS
AIRCRAFT CONTROL, UNSTEADY AERODYNAMICS;
PANEL METHODS; Aerodynamic control surfaces. (EDC)

15. NUMBER OF PAGES
15

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

90 05 25 151

Final Report on

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Grant No. AFOSR-85-0158

by

Dean T. Mook and Ali H. Nayfeh

Engineering Science and Mechanics Department
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

April 13, 1990

Aerodynamic/Dynamic Interaction

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This project involved a numerical/analytical development of simulations of the interactions among aerodynamics, dynamics, and control systems. A new unsteady vorticity-panel method, a new analytical model of wing rock, and new simulations of the response of vehicles to control-surface motions were developed. Three students received financial support directly from this project. Three others, who had scholarships, received support indirectly because D. Mook was free to advise them as a result of the support he received. There were four PhD's, one MS and one BS students who directly or indirectly received support from this project.

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A panel method based on continuous distributions of vorticity was developed. The vorticity representing the body may be viewed as an imitation of the boundary layer. With this method, the basic unknown is a primitive variable, rather than a potential. Specifically, the velocity vector is obtained directly without any post processing of the solution. Moreover, unlike other panel methods, the surface velocity, pressure, etc. are continuous functions; no singularities exist along the edges of the elements.

The vorticity-panel method was used to model flows past delta wings with flaps, among other applications. Then the resulting aerodynamic model was coupled with the equations of motion for a delta wing on a free-to-roll sting and

the resulting combination successfully simulated the wing-rock phenomenon. Finally, a feed-back control law, complete with inequality constraints, was added to the simulation and the simulation showed that it was possible to either enhance or eliminate the wing rock depending on the gains being used. This was was done by Captain Mracek for this PhD research.

Another student, working with D. Mook but supported by a scholarship, developed a numerical simulation of lifting surfaces in general unsteady ground effect. His simulation contained multiple lifting surfaces and control surfaces. Following an approach similar to Mracek's, he developed a simulation of a feed-back system to control pitch. The simulation shows significant differences in the performances in and out of ground effect.

An analytical model of wing-rock was developed, and critical comparisons among all the existing analytical models was made. The relevant publications are listed below.

A successful simulation of the response of a flexible wing (flutter) was developed by another student who also received a scholarship and was advised by D. Mook.

Some additional preliminary work on wing rock based on the vortex-lattice method was finished. And some work related to this effort, but involving two-dimensional flows, was begun. Publications and presentations stemming directly from this support and from spin-offs of this support are listed below.

II. Degrees Granted

1. Ph.D. - J. Elzebda, 1986 "A Numerical Model of Unsteady Aerodynamic Interference"

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3. Ph.D. - C. Mracek, 1988 "Unsteady Potential-Flow Solution by Vortex Panels Coupled with Dynamics and Controls"

4. Ph.D. - A. Nuhait, 1988 "Numerical Simulation of Feedback Control for Lifting Surfaces in Steady and Unsteady Ground Effects"

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6. Senior Project - S. Whitlock, (to be completed in 1990) "Numerical Simulation and Animation of Two-Dimensional Unsteady Lifting Flows"

III. Publications

1. **J. M. Elzebda, D. T. Mook, and A. H. Nayfeh, Steady and Unsteady Aerodynamic Interference in Closely Coupled Canard/Wing Configurations, Proceedings of the Forum on Unsteady Flow Separation, The 1987 ASME Applied Mechanics, Bioengineering, and Fluids Engineering Conference, Cincinnati, OH, June 14-17, 1987, FED Vol. 52, pp. 37-44.**

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2. **J. M. Elzebda, D. T. Mook, and A. H. Nayfeh, The Influence of an Additional Degree of Freedom on Subsonic Wing Rock of Slender Delta Wings, accepted for publication, Journal of Aircraft.**

The numerical simulation of the subsonic wing-rock phenomenon for slender delta wings is described. The present numerical model accounts for a second degree of freedom in pitch. According to the present simulation, there are two onset angles of attack: α_1 and α_2 where $\alpha_1 < \alpha_2$. When $\alpha < \alpha_1$, all initial perturbations decay and the wing is stable. When $\alpha_1 < \alpha < \alpha_2$, for all initial perturbations, the oscillation in pitch becomes very small, but a large-amplitude limit cycle develops in roll. The rolling motion is virtually identical to the motion for a single degree of freedom. When $\alpha > \alpha_2$, all initial disturbances lead to large-amplitude motions in both roll and pitch. The roll motion in this case differs markedly from the motion for a single degree of freedom: the growth rate is much lower and the period of the oscillations is slightly shorter for two degrees of freedom. Deviations in the pitch angle, when the wing is unstable, have both a steady and an oscillatory component. The present results suggest that the motion observed in the wind tunnel for the single-degree-of-freedom case differs significantly from the motion for the two-degree-of-freedom case; however, no wind-tunnel tests have been run to verify this. An earlier numerical simulation of the wing rock phenomenon for only one degree of freedom agreed very closely with two sets of experimental observation. *AIAA Paper No. 87-0496* .

3. **A. H. Nayfeh, J. M. Elzebda, and D. T. Mook, Analytical Study of the Subsonic Wing-Rock Phenomenon for Slender Delta Wings, Journal of Aircraft, Vol. 26, 1989, pp. 805-809.**

An analytic expression describing the aerodynamic roll moment has been obtained from the numerical simulation of wing rock. This expression is used in the equation governing the rolling motion of a delta wing around its mid-span axis. The result is used to construct phase planes which reveal the general global nature of wing rock--stable limit cycles, unstable foci, saddle points and domains of initial conditions leading to oscillatory

motion and divergence. An asymptotic approximation to the solution of the governing equation is obtained; this result provides expressions for the amplitudes and frequencies of limit cycles. The present analysis provides a penetrating global view of the wing-rock phenomenon.

Three analytical models of the subsonic wing-rock phenomenon for slender delta wings mounted on free-to-roll stings are compared. The first model was developed earlier by Hsu and Lan, the second is a version of the first model that has been modified in the present paper, and the third was developed in an earlier paper by the authors. The differences among the three models lie in the assumed nonlinear form of the roll moment as a function of the roll angle and its derivative. The numerical values of the coefficients in the moment expressions are obtained by fitting them to moments obtained in an earlier numerical simulation. It is shown that the original model of Hsu and Lan, which contains only quadratic terms, does not predict roll divergence. The model is modified by the addition of a cubic term, and the later in turn does predict roll divergence. An asymptotic approximation to the solution of the equation of motion is obtained for the modified model, and it is shown that the solution reduces to the one given by Hsu and Lan when the cubic term is dropped. Finally, the two models are compared with a third model developed earlier by the authors. The periods and amplitudes predicted by the asymptotic analysis for all three models are in close agreement with the numerical simulations, which were found in an earlier work to be in good agreement with experimental data. It appears that the authors' model is slightly more accurate and easier to analyze than either the model of Hsu and Lan or the modified version of their model.

4. **J. M. Elzebda, D. T. Mook, and A. H. Nayfeh, Influence of Pitching Motion on Subsonic Wing Rock of Slender Delta Wings, Journal of Aircraft, Vol. 26, 1989, pp. 503-508.**

A numerical simulation of the subsonic wing-rock phenomenon for slender delta wings is described. The present numerical model accounts for a second degree of freedom in pitch. According to the present

simulation, there are two onset angles of attack: $\alpha_1 < \alpha_2$. When $\alpha < \alpha_1$, all initial disturbances decay, and the wing is stable. When $\alpha_1 < \alpha < \alpha_2$, for all initial disturbances, the oscillation in pitch becomes very small, but a large-amplitude limit cycle develops in roll. The rolling motion is virtually identical to the motion for a single degree of freedom in roll. When $\alpha > \alpha_2$, all initial disturbances lead to large-amplitude motions in both roll and pitch. The roll motion in this case differs markedly from the motion for a single degree of freedom. The present results suggest that the motion observed in the wind tunnel for the single-degree-of-freedom case differs significantly from the motion for the two-degree-of-freedom case. The numerical simulation of the wing-rock phenomenon for only one degree of freedom agrees very closely with two sets of experimental observations.

5. **C. P. Mracek, M. J. Kim, and D. T. Mook, "Numerical Solution of Three Dimensional Potential Flow Using a Vortex Panel Method," accepted for publication Computers and Fluids.**

An alternate approach for predicting incompressible, potential flow over closed bodies is presented. The method uses triangular panels of linearly varying surface velocity. The velocities at the vertices of the triangles are obtained by minimizing the flow through the body at control points subject to the constraint that the vortex field is divergenceless. The results obtained by the present method show good agreement with analytical solutions for a variety of spheroids. The method is robust in that the solution converges as the number of elements is increased. Some desirable featùres of this method are that the elements are planar, the unknown velocity components are on the actual surface of the body and the unknowns of the problem are primitive variables.

6. **D. T. Mook, S. Roy, G. Choksi, and B. Dong, "On the Numerical Simulation of the Unsteady Wake Behind an Airfoil," Journal of Aircraft, Vol. 26, No. 6, 1989, pp. 509-514.**

The unsteady wake behind an airfoil is simulated numerically by a system of discrete vortex cores, also called point vortices. In common with

previously developed procedures, at each time step a core is added to the wake at the trailing edge, and the cores already in the wake are convected at the local particle velocity. The innovation of the present method is that, as the cores begin to separate, more cores are added to the system and the circulations around the individual cores are reduced according to a linear interpolation routine. The spacing between cores is maintained approximately while the total circulation around the wake and airfoil is maintained exactly. In several examples, one finds qualitative agreement between computed wake shapes and flow visualization. The method shows promise as a means of simulating unsteady, closely-coupled aerodynamic interference.

7. **T. W. Strganac and D. T. Mook, "A Numerical Model of Unsteady Subsonic Aeroelastic Behavior," accepted for publication AIAA Journal.**

The present paper describes a numerical simulation of unsteady subsonic aeroelastic responses. The technique accounts for aerodynamic nonlinearities associated with angles of attack, vortex-dominated flow, static deformations, and unsteady behavior. The fluid and the wing together are treated as single dynamic system, and the equations of motion for the structure and flowfield are integrated simultaneously and interactively in the time domain. The method employs an iterative scheme based on a predictor-corrector technique. The aerodynamic loads are computed by the general unsteady vortex-lattice method and are determined simultaneously with the motion of the wing. Two models are used to demonstrate the technique; a rigid wing on an elastic support experiencing plunge and pitch about the elastic axis, and an elastic wing rigidly supported at the root chord experiencing spanwise bending and twisting.

8. **J. M. Elzebda, A. H. Nayfeh, and D. T. Mook, "Development of an Analytical Model of Wing Rock for Slender Delta Wings," Journal of Aircraft, Vol. 26, No. 8, 1989, pp. 737-743.**

Three analytical models of the subsonic wing-rock phenomenon for slender delta wings mounted on free-to-roll stings are compared. The first model was developed earlier by Hsu and Lan, the second is a version of the first model that has been modified in the present paper, and the third was developed in an earlier paper by the authors. The differences among the three models lie in the assumed nonlinear form of the roll moment as a function of the roll angle and its derivative. The numerical values of the coefficients in the moment expressions are obtained by fitting them to moments obtained in an earlier numerical simulation. It is shown that the original model of Hsu and Lan, which contains only quadratic terms, does not predict roll divergence. The model is modified by the addition of a cubic term, and the later in turn does predict roll divergence. An asymptotic approximation to the solution of the equation of motion is obtained for the modified model, and it is shown that the solution reduces to the one given by Hsu and Lan when the cubic term is dropped. Finally, the two models are compared with a third model developed earlier by the authors. The periods and amplitudes predicted by the asymptotic analysis for all three models are in close agreement with the numerical simulations, which were found in an earlier work to be in good agreement with experimental data. It appears that the authors' model is slightly more accurate and easier to analyze than either the model of Hsu and Lan or the modified version of their model.

9. **B. Dong and D. T. Mook, "Numerical Simulation of Blade-Vortex Interaction," submitted for publication AIAA Journal.**

Blade-vortex interaction is investigated in two ways. First, the interaction between a single point vortex and a blade is modelled. The ground effect on the interaction is considered for this model. Second, the interaction between the wake of an oscillating airfoil and a fixed blade is modelled. In both, the flow is considered two-dimensional, inviscid and incompressible. Some results are found to be in close agreement with various solutions of others. However, the present numerical simulation of an earlier experiment is not in agreement with the experiment. Reasons

are given for believing that separation occurred in the experiment. The present numerical model is based on the assumption that the flow is always attached.

10. **D. T. Mook and A. O. Nuhait, "Numerical Simulation of Wings in Steady and Unsteady Ground Effects," Vol. 26, No. 12, 1989, pp. 1081-1089.**

During take-off and landing, the aerodynamic characteristics of an airplane are strongly influenced by the proximity of the ground. This phenomenon is called ground effect. The landing and take off are critical phases in a flight. As a result extensive research, both theoretical and experimental, has been devoted to understanding and predicting the ground effect.

11. **D. T. Mook and B. Dong, "Application of Vortex Dynamics to Simulations of Two-Dimensional Wakes," submitted for publication ASME Journal of Fluids Engineering.**

A method for simulating flows past solid bodies and their wakes is described. Vorticity panels are used to represent the body, and vortex blobs (point vortices with their singularities removed) are used to present the wake. The procedure is applied to the simulation of completely attached flow past an oscillating airfoil. The rate at which vorticity is shed from the trailing edge is determined by simultaneously requiring the pressures along the upper and lower surface streamlines to approach the same value at the trailing edge and the circulation around both the airfoil and its wake to remain constant. The motion of the airfoil is discretized, and one vortex blob is shed from the trailing edge at each time step. The vortex blobs are convected at the local particle velocity, a procedure that renders the pressure continuous in an inviscid fluid. When the blobs begin to separate they are split, and when they begin to collect they are combined. The numerical simulation reveals that the wake, which is originally smooth, eventually coils, or wraps, around itself, primarily under the influence of the velocity it induces on itself, and forms so-called vortical structures (regions of relatively concentrated vorticity.) Although discrete

blobs are used to represent the wake, the velocity profiles across a typical vortical structure are smooth. Although the computed wake evolves in an entirely inviscid model of the flowfield, these velocity profiles appear to have a viscous core at their center. The computed spacing of the vortical structures and the circulations around them are in good agreement with experimental results. A simulation of the interaction between vorticity in the oncoming stream and a stationary airfoil is also discussed.

IV. Presentations

1. P. Konstadinopoulos, D. T. Mook, and A. H. Nayfeh, "Subsonic Wing Rock of Slender Delta Wings," presented at the AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 1985.

2. M. J. Kim and D. T. Mook, "Application of Continuous Vorticity Panels to General Unsteady 2-D Lifting Flows," presented at the 23rd Aerospace Sciences Meeting, Reno, NV, January 1985.

3. D. T. Mook, "Subsonic Wing-Rock Phenomenon," seminar presented at Texas A&M University, April 1985.

4. J. Elzebda, D. T. Mook, and A. H. Nayfeh, "Unsteady Aerodynamic Interference for Lifting Surfaces," presented at the AIAA Flight Mechanics Conference, Snowmass, CO, August 1985, AIAA Paper No. 85-1801-CP.

5. D. T. Mook and A. H. Nayfeh, "Application of the Vortex-Lattice Method to High-Angle-of-Attack Aerodynamics," presented at the SAE Aerospace Technology Conference, San Diego, CA, October 1985, SAE Paper No. 851817.

6. D. T. Mook, "Application of the Vortex-Lattice Method to Simulate Subsonic Aerodynamic Interference," seminar presented at Grumman Aerospace Corporation, Bethpage, Long Island, NY, March 1986.

7. T. Strganac and D. T. Mook, "Application of the Unsteady Vortex-Lattice Method to the Nonlinear Two-Degree-of-Freedom Aeroelastic Equations," AIAA Paper No. 86-0867-CP, presented at the AIAA/ASME/ASCE/AHS 27th Structures, Structural Dynamics, and Materials Conference, San Antonio, TX, May 19-21, 1986.

8. J. Elzebda, D. T. Mook, and A. H. Nayfeh, "A Numerical Model of Unsteady Aerodynamic Interference," presented at the 10th U.S. Congress of Applied Mechanics, Austin, TX, June 1986.

9. Jamal Elzebda, Dean T. Mook, and Ali H. Nayfeh, "Numerical Simulation of Unsteady Aerodynamic Interference," presented at the 39th Annual Meeting of the Division of Fluid Mechanics, American Physical Society, Columbus, OH, November 1986.

10. Jamal Elzebda, Dean T. Mook, and Ali H. Nayfeh, "Aerodynamic/Dynamic Interaction," presented at the 39th Annual Meeting of the Division of Fluid Mechanics, American Physical Society, Columbus, OH, November 1986.

11. D. T. Mook, "Aerodynamic/Dynamic Interaction," seminar presented at the Mechanical Engineering Department, Washington State University, December 1986.

12. J. .M. Elzebda, D. T. Mook, and A. H. Nayfeh, "The Influence of an Additional Degree of Freedom on Subsonic Wing Rock of Slender Delta Wings," AIAA Paper No. 87-0496, presented at the Fluid Dynamics AIAA 25th Aerospace Sciences Meeting, Reno, NV, January 12-15, 1987.

13. D. T. Mook, "Aerodynamic/Dynamic Interaction," invited seminar presented at the Aerospace Engineering Department, Ohio State University, January 21, 1987.

14. T. W. Strganac and D. T. Mook, "A New Method to Predict Unsteady Aeroelastic Behavior," AIAA Paper No. 87-0736-CP, presented at the AIAA/ASME/ASCE/AHS 28th Structures, Structural Dynamics and Materials Conference, Monterey, CA, April 6-8, 1987.

15. T. W. Strganac, D. T. Mook, and M. V. Mitchum, "The Numerical Simulation of Subsonic Flutter," AIAA Paper No. 87-1428, presented at the AIAA 19th Fluid Dynamics, Plasma Dynamics and Lasers Conference, Honolulu, Hawaii, June 8-10, 1987.

16. J. Elzebda, D. T. Mook, and A. H. Nayfeh, "Steady and Unsteady Aerodynamic Interference in Closely Coupled Canard/Wing Configurations," presented at the Forum on Unsteady Flow Separation, The 1987 ASME Applied Mechanics, Bioengineering, and Fluid Engineering Spring Conference, Cincinnati, OH, June 1987, FED Vol. 52, pp. 37-44.

17. D. T. Mook and T. W. Strganac, "Numerical Simulation of Subsonic Flutter," invited seminar at NASA Langley Research Center, Hampton, VA, June 23, 1987.

18. Dean T. Mook and A. H. Nayfeh, "Dynamic/Aerodynamic Interaction," presented at the AFOSR Workshop to Review Sponsored Research on Unsteady Separated Flows, Colorado Springs, CO, July 1987.

19. T. W. Strganac and D. T. Mook, "Nonlinear Dynamic/Aerodynamic Interaction with Applications to the Numerical Simulation of Flutter," presented at the Second Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, Boca Raton, FL, November 18-20, 1987.

20. D. T. Mook, S. Roy, G. Choksi, and B. Dong., "On the Numerical Simulation of the Unsteady Wake Behind an Airfoil," presented at the 25th Aerospace Sciences Meeting, Reno, NV, AIAA Paper No. 87-0190.

21. D. T. Mook, "Transient Behavior of Lifting Surfaces in Ground Effect," invited seminar, CALSPAN Corporation, Buffalo, NY, March 1988.

22. D. T. Mook, "Unsteady Aerodynamics," an invited series of three lectures presented at the Von Karman Institute, Brussels, Belgium, April 1988.

23. D. T. Mook, "Aerodynamic/Dynamic/Control Interaction," seminar presented at Wright-Patterson Air Force Base, OH, September 1988.

24. A. O. Nuhait and D. T. Mook, "Numerical Simulation of Wings in Steady and Unsteady Ground Effects," presented at the AIAA Applied Aerodynamics Conference, Williamsburg, VA, June 1988, AIAA Paper No. 88-2546, in Collection of Technical Paper, pp. 246-257.

25. C. P. Mracek and D. T. Mook, "Numerical Simulation of Three-Dimensional Lifting Flows by a Vortex Panel Method," presented at the AIAA Flight Mechanics Conference, Minneapolis, MN, August 1988, AIAA Paper No. 88-4335-CP.

26. M. J. Kim and D. T. Mook, "Application of Continuous Vorticity Panels in Steady Three-Dimensional Lifting Flows with Partial Separation, presented at the 27th Aerospace Sciences Meeting, Reno, NV, January 1989, AIAA Paper No. 89-0117.

27. D. T. Mook and A. O. Nuhait, "Simulation of the Interaction Between Aerodynamics and Vehicle Dynamics in General Unsteady Ground Effect," AIAA Paper No. 89-1498, presented at the Intersociety Advanced Marine Vehicles Conference, Washington, DC, June 1989.

28. B. Dong and D. T. Mook, "Numerical Simulation of Wakes with Application to Blade-Vortex Interaction" invited paper presented at the Third International Congress of Fluid Mechanics, Cairo, Egypt, January 2-4, 1990.

29. B. Dong and D. T. Mook, "Numerical Simulation of Unsteady Aeroelastic Behavior," presented at the SECTAM XV 1990 Southeastern Conference on Theoretical and Applied Mechanics, Atlanta, GA, March 22-23, 1990.

30. D. T. Mook and B. Dong, "Application of Vortex Dynamics to Simulations of Two-Dimensional Wakes," invited paper to be presented at the Joint ASME/CSME Symposium on Nonsteady Fluid Dynamics, Toronto, Canada, June 4-7, 1990.

31. D. T. Mook and A. H. Nayfeh, "Numerical Simulations of Dynamic/Aerodynamic Interaction," to be presented at the Symposium on Computational Technology for Flight Vehicles, Washington, DC, November 5-7, 1990.

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   A versatile method based on the general unsteady vortex-lattice technique was developed in a previous paper. This method models flows over an arbitrary number of lifting surfaces. Further use of this method is considered in this paper. The X-29 (two canards and main wing) is used as a model, and simulations of the steady and unsteady aerodynamic interference are presented. A comparison of the static aerodynamic load with wind-tunnel data shows good agreement. The present investigation also yields the time histories of the aerodynamic loads on the lifting surfaces for a sinusoidal motion. The results show the strong influence of the canards on the main wing, including the time lag between the motion of the canards and the subsequent changes in the pressure distributions and loads on the main wing.

2. **J. M. Elzebda, D. T. Mook, and A. H. Nayfeh, The Influence of an Additional Degree of Freedom on Subsonic Wing Rock of Slender Delta Wings, accepted for publication, Journal of Aircraft.**

The numerical simulation of the subsonic wing-rock phenomenon for slender delta wings is described. The present numerical model accounts for a second degree of freedom in pitch. According to the present simulation, there are two onset angles of attack: α_1 and α_2 where $\alpha_1 < \alpha_2$. When $\alpha < \alpha_1$, all initial perturbations decay and the wing is stable. When $\alpha_1 < \alpha < \alpha_2$, for all initial perturbations, the oscillation in pitch becomes very small, but a large-amplitude limit cycle develops in roll. The rolling motion is virtually identical to the motion for a single degree of freedom. When $\alpha > \alpha_2$, all initial disturbances lead to large-amplitude motions in both roll and pitch. The roll motion in this case differs markedly from the motion for a single degree of freedom: the growth rate is much lower and the period of the oscillations is slightly shorter for two degrees of freedom. Deviations in the pitch angle, when the wing is unstable, have both a steady and an oscillatory component. The present results suggest that the motion observed in the wind tunnel for the single-degree-of-freedom case differs significantly from the motion for the two-degree-of-freedom case; however, no wind-tunnel tests have been run to verify this. An earlier numerical simulation of the wing rock phenomenon for only one degree of freedom agreed very closely with two sets of experimental observation. *AIAA Paper No. 87-0496* .

3. **A. H. Nayfeh, J. M. Elzebda, and D. T. Mook, Analytical Study of the Subsonic Wing-Rock Phenomenon for Slender Delta Wings, Journal of Aircraft, Vol. 26, 1989, pp. 805-809.**

An analytic expression describing the aerodynamic roll moment has been obtained from the numerical simulation of wing rock. This expression is used in the equation governing the rolling motion of a delta wing around its mid-span axis. The result is used to construct phase planes which reveal the general global nature of wing rock--stable limit cycles, unstable foci, saddle points and domains of initial conditions leading to oscillatory

motion and divergence. An asymptotic approximation to the solution of the governing equation is obtained; this result provides expressions for the amplitudes and frequencies of limit cycles. The present analysis provides a penetrating global view of the wing-rock phenomenon.

Three analytical models of the subsonic wing-rock phenomenon for slender delta wings mounted on free-to-roll stings are compared. The first model was developed earlier by Hsu and Lan, the second is a version of the first model that has been modified in the present paper, and the third was developed in an earlier paper by the authors. The differences among the three models lie in the assumed nonlinear form of the roll moment as a function of the roll angle and its derivative. The numerical values of the coefficients in the moment expressions are obtained by fitting them to moments obtained in an earlier numerical simulation. It is shown that the original model of Hsu and Lan, which contains only quadratic terms, does not predict roll divergence. The model is modified by the addition of a cubic term, and the later in turn does predict roll divergence. An asymptotic approximation to the solution of the equation of motion is obtained for the modified model, and it is shown that the solution reduces to the one given by Hsu and Lan when the cubic term is dropped. Finally, the two models are compared with a third model developed earlier by the authors. The periods and amplitudes predicted by the asymptotic analysis for all three models are in close agreement with the numerical simulations, which were found in an earlier work to be in good agreement with experimental data. It appears that the authors' model is slightly more accurate and easier to analyze than either the model of Hsu and Lan or the modified version of their model.

4. **J. M. Elzebda, D. T. Mook, and A. H. Nayfeh, Influence of Pitching Motion on Subsonic Wing Rock of Slender Delta Wings, Journal of Aircraft, Vol. 26, 1989, pp. 503-508.**

A numerical simulation of the subsonic wing-rock phenomenon for slender delta wings is described. The present numerical model accounts for a second degree of freedom in pitch. According to the present

simulation, there are two onset angles of attack: $\alpha_1 < \alpha_2$. When $\alpha < \alpha_1$, all initial disturbances decay, and the wing is stable. When $\alpha_1 < \alpha < \alpha_2$, for all initial disturbances, the oscillation in pitch becomes very small, but a large-amplitude limit cycle develops in roll. The rolling motion is virtually identical to the motion for a single degree of freedom in roll. When $\alpha > \alpha_2$, all initial disturbances lead to large-amplitude motions in both roll and pitch. The roll motion in this case differs markedly from the motion for a single degree of freedom. The present results suggest that the motion observed in the wind tunnel for the single-degree-of-freedom case differs significantly from the motion for the two-degree-of-freedom case. The numerical simulation of the wing-rock phenomenon for only one degree of freedom agrees very closely with two sets of experimental observations.

5. **C. P. Mracek, M. J. Kim, and D. T. Mook, "Numerical Solution of Three Dimensional Potential Flow Using a Vortex Panel Method," accepted for publication Computers and Fluids.**

An alternate approach for predicting incompressible, potential flow over closed bodies is presented. The method uses triangular panels of linearly varying surface velocity. The velocities at the vertices of the triangles are obtained by minimizing the flow through the body at control points subject to the constraint that the vortex field is divergenceless. The results obtained by the present method show good agreement with analytical solutions for a variety of spheroids. The method is robust in that the solution converges as the number of elements is increased. Some desirable features of this method are that the elements are planar, the unknown velocity components are on the actual surface of the body and the unknowns of the problem are primitive variables.

6. **D. T. Mook, S. Roy, G. Choksi, and B. Dong, "On the Numerical Simulation of the Unsteady Wake Behind an Airfoil," Journal of Aircraft, Vol. 26, No. 6, 1989, pp. 509-514.**

The unsteady wake behind an airfoil is simulated numerically by a system of discrete vortex cores, also called point vortices. In common with

previously developed procedures, at each time step a core is added to the wake at the trailing edge, and the cores already in the wake are convected at the local particle velocity. The innovation of the present method is that, as the cores begin to separate, more cores are added to the system and the circulations around the individual cores are reduced according to a linear interpolation routine. The spacing between cores is maintained approximately while the total circulation around the wake and airfoil is maintained exactly. In several examples, one finds qualitative agreement between computed wake shapes and flow visualization. The method shows promise as a means of simulating unsteady, closely-coupled aerodynamic interference.

7. **T. W. Strganac and D. T. Mook, "A Numerical Model of Unsteady Subsonic Aeroelastic Behavior," accepted for publication AIAA Journal.**

The present paper describes a numerical simulation of unsteady subsonic aeroelastic responses. The technique accounts for aerodynamic nonlinearities associated with angles of attack, vortex-dominated flow, static deformations, and unsteady behavior. The fluid and the wing together are treated as single dynamic system, and the equations of motion for the structure and flowfield are integrated simultaneously and interactively in the time domain. The method employs an iterative scheme based on a predictor-corrector technique. The aerodynamic loads are computed by the general unsteady vortex-lattice method and are determined simultaneously with the motion of the wing. Two models are used to demonstrate the technique; a rigid wing on an elastic support experiencing plunge and pitch about the elastic axis, and an elastic wing rigidly supported at the root chord experiencing spanwise bending and twisting.

8. **J. M. Elzebda, A. H. Nayfeh, and D. T. Mook, "Development of an Analytical Model of Wing Rock for Slender Delta Wings," Journal of Aircraft, Vol. 26, No. 8, 1989, pp. 737-743.**

Three analytical models of the subsonic wing-rock phenomenon for slender delta wings mounted on free-to-roll stings are compared. The first model was developed earlier by Hsu and Lan, the second is a version of the first model that has been modified in the present paper, and the third was developed in an earlier paper by the authors. The differences among the three models lie in the assumed nonlinear form of the roll moment as a function of the roll angle and its derivative. The numerical values of the coefficients in the moment expressions are obtained by fitting them to moments obtained in an earlier numerical simulation. It is shown that the original model of Hsu and Lan, which contains only quadratic terms, does not predict roll divergence. The model is modified by the addition of a cubic term, and the later in turn does predict roll divergence. An asymptotic approximation to the solution of the equation of motion is obtained for the modified model, and it is shown that the solution reduces to the one given by Hsu and Lan when the cubic term is dropped. Finally, the two models are compared with a third model developed earlier by the authors. The periods and amplitudes predicted by the asymptotic analysis for all three models are in close agreement with the numerical simulations, which were found in an earlier work to be in good agreement with experimental data. It appears that the authors' model is slightly more accurate and easier to analyze than either the model of Hsu and Lan or the modified version of their model.

9. **B. Dong and D. T. Mook, "Numerical Simulation of Blade-Vortex Interaction," submitted for publication AIAA Journal.**

Blade-vortex interaction is investigated in two ways. First, the interaction between a single point vortex and a blade is modelled. The ground effect on the interaction is considered for this model. Second, the interaction between the wake of an oscillating airfoil and a fixed blade is modelled. In both, the flow is considered two-dimensional, inviscid and incompressible. Some results are found to be in close agreement with various solutions of others. However, the present numerical simulation of an earlier experiment is not in agreement with the experiment. Reasons

are given for believing that separation occurred in the experiment. The present numerical model is based on the assumption that the flow is always attached.

10. **D. T. Mook and A. O. Nuhait, "Numerical Simulation of Wings in Steady and Unsteady Ground Effects," Vol. 26, No. 12, 1989, pp. 1081-1089.**

During take-off and landing, the aerodynamic characteristics of an airplane are strongly influenced by the proximity of the ground. This phenomenon is called ground effect. The landing and take off are critical phases in a flight. As a result extensive research, both theoretical and experimental, has been devoted to understanding and predicting the ground effect.

11. **D. T. Mook and B. Dong, "Application of Vortex Dynamics to Simulations of Two-Dimensional Wakes," submitted for publication ASME Journal of Fluids Engineering.**

A method for simulating flows past solid bodies and their wakes is described. Vorticity panels are used to represent the body, and vortex blobs (point vortices with their singularities removed) are used to present the wake. The procedure is applied to the simulation of completely attached flow past an oscillating airfoil. The rate at which vorticity is shed from the trailing edge is determined by simultaneously requiring the pressures along the upper and lower surface streamlines to approach the same value at the trailing edge and the circulation around both the airfoil and its wake to remain constant. The motion of the airfoil is discretized, and one vortex blob is shed from the trailing edge at each time step. The vortex blobs are convected at the local particle velocity, a procedure that renders the pressure continuous in an inviscid fluid. When the blobs begin to separate they are split, and when they begin to collect they are combined. The numerical simulation reveals that the wake, which is originally smooth, eventually coils, or wraps, around itself, primarily under the influence of the velocity it induces on itself, and forms so-called vortical structures (regions of relatively concentrated vorticity.) Although discrete

blobs are used to represent the wake, the velocity profiles across a typical vortical structure are smooth. Although the computed wake evolves in an entirely inviscid model of the flowfield, these velocity profiles appear to have a viscous core at their center. The computed spacing of the vortical structures and the circulations around them are in good agreement with experimental results. A simulation of the interaction between vorticity in the oncoming stream and a stationary airfoil is also discussed.

IV. Presentations

1. P. Konstadinopoulos, D. T. Mook, and A. H. Nayfeh, "Subsonic Wing Rock of Slender Delta Wings," presented at the AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 1985.

2. M. J. Kim and D. T. Mook, "Application of Continuous Vorticity Panels to General Unsteady 2-D Lifting Flows," presented at the 23rd Aerospace Sciences Meeting, Reno, NV, January 1985.

3. D. T. Mook, "Subsonic Wing-Rock Phenomenon," seminar presented at Texas A&M University, April 1985.

4. J. Elzebda, D. T. Mook, and A. H. Nayfeh, "Unsteady Aerodynamic Interference for Lifting Surfaces," presented at the AIAA Flight Mechanics Conference, Snowmass, CO, August 1985, AIAA Paper No. 85-1801-CP.

5. D. T. Mook and A. H. Nayfeh, "Application of the Vortex-Lattice Method to High-Angle-of-Attack Aerodynamics," presented at the SAE Aerospace Technology Conference, San Diego, CA, October 1985, SAE Paper No. 851817.

6. D. T. Mook, "Application of the Vortex-Lattice Method to Simulate Subsonic Aerodynamic Interference," seminar presented at Grumman Aerospace Corporation, Bethpage, Long Island, NY, March 1986.

7. T. Strganac and D. T. Mook, "Application of the Unsteady Vortex-Lattice Method to the Nonlinear Two-Degree-of-Freedom Aeroelastic Equations," AIAA Paper No. 86-0867-CP, presented at the AIAA/ASME/ASCE/AHS 27th Structures, Structural Dynamics, and Materials Conference, San Antonio, TX, May 19-21, 1986.

8. J. Elzebda, D. T. Mook, and A. H. Nayfeh, "A Numerical Model of Unsteady Aerodynamic Interference," presented at the 10th U.S. Congress of Applied Mechanics, Austin, TX, June 1986.

9. Jamal Elzebda, Dean T. Mook, and Ali H. Nayfeh, "Numerical Simulation of Unsteady Aerodynamic Interference," presented at the 39th Annual Meeting of the Division of Fluid Mechanics, American Physical Society, Columbus, OH, November 1986.

10. Jamal Elzebda, Dean T. Mook, and Ali H. Nayfeh, "Aerodynamic/Dynamic Interaction," presented at the 39th Annual Meeting of the Division of Fluid Mechanics, American Physical Society, Columbus, OH, November 1986.

11. D. T. Mook, "Aerodynamic/Dynamic Interaction," seminar presented at the Mechanical Engineering Department, Washington State University, December 1986.

12. J. .M. Elzebda, D. T. Mook, and A. H. Nayfeh, "The Influence of an Additional Degree of Freedom on Subsonic Wing Rock of Slender Delta Wings," AIAA Paper No. 87-0496, presented at the Fluid Dynamics AIAA 25th Aerospace Sciences Meeting, Reno, NV, January 12-15, 1987.

13. D. T. Mook, "Aerodynamic/Dynamic Interaction," invited seminar presented at the Aerospace Engineering Department, Ohio State University, January 21, 1987.

14. T. W. Strganac and D. T. Mook, "A New Method to Predict Unsteady Aeroelastic Behavior," AIAA Paper No. 87-0736-CP, presented at the AIAA/ASME/ASCE/AHS 28th Structures, Structural Dynamics and Materials Conference, Monterey, CA, April 6-8, 1987.

15. T. W. Strganac, D. T. Mook, and M. V. Mitchum, "The Numerical Simulation of Subsonic Flutter," AIAA Paper No. 87-1428, presented at the AIAA 19th Fluid Dynamics, Plasma Dynamics and Lasers Conference, Honolulu, Hawaii, June 8-10, 1987.

16. J. Elzebda, D. T. Mook, and A. H. Nayfeh, "Steady and Unsteady Aerodynamic Interference in Closely Coupled Canard/Wing Configurations," presented at the Forum on Unsteady Flow Separation, The 1987 ASME Applied Mechanics, Bioengineering, and Fluid Engineering Spring Conference, Cincinnati, OH, June 1987, FED Vol. 52, pp. 37-44.

17. D. T. Mook and T. W. Strganac, "Numerical Simulation of Subsonic Flutter," invited seminar at NASA Langley Research Center, Hampton, VA, June 23, 1987.

18. Dean T. Mook and A. H. Nayfeh, "Dynamic/Aerodynamic Interaction," presented at the AFOSR Workshop to Review Sponsored Research on Unsteady Separated Flows, Colorado Springs, CO, July 1987.

19. T. W. Strganac and D. T. Mook, "Nonlinear Dynamic/Aerodynamic Interaction with Applications to the Numerical Simulation of Flutter," presented at the Second Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, Boca Raton, FL, November 18-20, 1987.

20. D. T. Mook, S. Roy, G. Choksi, and B. Dong., "On the Numerical Simulation of the Unsteady Wake Behind an Airfoil," presented at the 25th Aerospace Sciences Meeting, Reno, NV, AIAA Paper No. 87-0190.

21. D. T. Mook, "Transient Behavior of Lifting Surfaces in Ground Effect," invited seminar, CALSPAN Corporation, Buffalo, NY, March 1988.

22. D. T. Mook, "Unsteady Aerodynamics," an invited series of three lectures presented at the Von Karman Institute, Brussels, Belgium, April 1988.

23. D. T. Mook, "Aerodynamic/Dynamic/Control Interaction," seminar presented at Wright-Patterson Air Force Base, OH, September 1988.

24. A. O. Nuhait and D. T. Mook, "Numerical Simulation of Wings in Steady and Unsteady Ground Effects," presented at the AIAA Applied Aerodynamics Conference, Williamsburg, VA, June 1988, AIAA Paper No. 88-2546, in Collection of Technical Paper, pp. 246-257.

25. C. P. Mracek and D. T. Mook, "Numerical Simulation of Three-Dimensional Lifting Flows by a Vortex Panel Method," presented at the AIAA Flight Mechanics Conference, Minneapolis, MN, August 1988, AIAA Paper No. 88-4335-CP.

26. M. J. Kim and D. T. Mook, "Application of Continuous Vorticity Panels in Steady Three-Dimensional Lifting Flows with Partial Separation, presented at the 27th Aerospace Sciences Meeting, Reno, NV, January 1989, AIAA Paper No. 89-0117.

27. D. T. Mook and A. O. Nuhait, "Simulation of the Interaction Between Aerodynamics and Vehicle Dynamics in General Unsteady Ground Effect," AIAA Paper No. 89-1498, presented at the Intersociety Advanced Marine Vehicles Conference, Washington, DC, June 1989.

28. B. Dong and D. T. Mook, "Numerical Simulation of Wakes with Application to Blade-Vortex Interaction" invited paper presented at the Third International Congress of Fluid Mechanics, Cairo, Egypt, January 2-4, 1990.

29. B. Dong and D. T. Mook, "Numerical Simulation of Unsteady Aeroelastic Behavior," presented at the SECTAM XV 1990 Southeastern Conference on Theoretical and Applied Mechanics, Atlanta, GA, March 22-23, 1990.

30. D. T. Mook and B. Dong, "Application of Vortex Dynamics to Simulations of Two-Dimensional Wakes," invited paper to be presented at the Joint ASME/CSME Symposium on Nonsteady Fluid Dynamics, Toronto, Canada, June 4-7, 1990.

31. D. T. Mook and A. H. Nayfeh, "Numerical Simulations of Dynamic/Aerodynamic Interaction," to be presented at the Symposium on Computational Technology for Flight Vehicles, Washington, DC, November 5-7, 1990.